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The Shocking Development of Lithium (and Boron) in Supernovae

David S. P. Dearborn
Lawrence Livermore National Lab.

David N. Schramm
University of Chicago and
NASA/Fermilab Astrophysics Center

Gary Steigman
Ohio State University

James Truran
University of Illinois

ABSTRACT

It is shown that significant amounts of ^{7} Li and ^{11}B are produced in Type II supernovae. The synthesis of these rare elements occurs as the supernova shock traverses the base of the hydrogen envelope burning ^{3}He to masses 7 and 11 via alpha capture. The yields in this process are sufficient to account for the difference in lithium abundance observed between Pop II and Pop I stars. Since lithium (and boron) would, in this manner, be created in the same stars that produce the bulk of the heavy elements, the lithium abundance even in old Pop I stars would be high (as observed). The ^{11}B production may remedy the long-standing problem of the traditional spallation scenario to account for the observed isotopic ratio of boron. Observational consequences of this mechanism are discussed, including the evolution of lithium and boron isotope ratios in the Galaxy and the possible use of the boron yields to constrain the number of blue progenitor Type II supernovae.

INTRODUCTION

In recent years lithium has played an increasingly important role in the cosmological arena. Within the context of standard Big Bang Nucleosythesis, the primordial abundance of lithium provides an important constraint on the universal density of nucleons (Kawano, Schramm and Steigman, 1987). The primordial abundance of lithium can also be used to discriminate among non-standard cosmological models such as inhomogeneous models (Applegate, Hogan and Scherrer 1987; Alcock, Fuller and Mathews 1987).

The major obstacle to utilizing lithium as a cosmological barometer is the uncertainty in determining its primordial abundance. If the low value observed in Pop II stars (Spite and Spite 1982; Spite, Maillard and Spite 1984; Hobbs and Duncan 1987; Rebolo, Molaro and Beckman 1988; Hobbs and Pilachowski 1988a)

$$[Li]_{PopII} = 2.1 \pm 0.2, \tag{1}$$

is representative of the primordial value, then it becomes a crucial astrophysical issue to account for the high abundance observed in Pop I stars and the interstellar medium (Boesgaard, Budge and Ramsay 1988; Hobbs and Pilachowski 1986, 1988b)

$$[Li]_{PopI} = 3.1 \pm 0.2 \tag{2}$$

In (1) and (2), $[Li] \equiv 12 + log(Li/H)$. Constraints on the origin of the Pop I lithium abundance are made more severe by the recent observations of Hobbs and Pilachowski (1988a) that the oldest Pop I stars have the same high lithium abundance as do the youngest Pop I stars (note, however, that the age of the Hobbs and Pilachowski stars have been called into question by Twarog and Twarog 1988). This data then implies that the lithium abundance must have increased rapidly so that when $[Fe/H] \approx 0, [Li] \approx [Li]_{PopII}$. This suggests we look to shortlived, relatively massive stars for the origin of Pop I lithium.

Previously proposed lithium production mechanisms have been cosmic ray spallation (Reeves, Fowler and Hoyle, 1970), red giant production (Cameron and Fowler, 1971), and production in novae (Starrfield, et al. 1988). However, cosmic ray spallation produces ^7Li and ^6Li in the ratio $^7Li/^6Li \sim 2$ (Walker, Mathews and Viola 1985) whereas solar system observations (Cameron 1982) yield $^7Li/^6Li \sim 12$ in agreement with the lower bound of $^7Li/^6Li \gtrsim 10$ in F and G stars determined by Anderson, Gustafsson and Lambert (1984); for the interstellar medium towards Zeta Ophiuchus, Ferlet and Dennefeld (1984) find $^7Li/^6Li \sim 38$ ($\gtrsim 25$). (However, this direction looks through the Sco-Cen Association region which has had many recent supernova and is probably not a typical ISM sample.) Thus, if spallation produces the observed Pop I ^6Li, it under produces the observed ^7Li. Thus an additional source of ^7Li is needed. The red giant mechanism occurs in intermediate mass stars so it may not yield Li abundances which rise as rapidly with time as the abundances of the bulk of the heavy elements do.

In this paper we propose that standard massive star ($M \gtrsim 10\ M_{\odot}$) core collapse supernovae (Type II's ?) produce Lithium (and Boron) as the supernova shock hits the hydrogen envelope. In particular, the ^3He remaining in the inner part of the hydrogen envelope will be burned with the ambient ^4He via ($^3He(\alpha\gamma)^7Be$) as the shock heats ($T \sim 2-3 \times 10^8 K$) the material. The ejected ^7Be will decay to ^7Li in the lower temperature, lower density dispersed envelope so that the ^7Li is not destroyed. This is similar to the Cameron and Fowler (1971) red giant mechanism where convection was used to move the

^7Be out to the lower temperatures , but here the shock not only moves the ^7Be but also does the heating.

An interesting and important consequence of this mechanism is that ^{11}B is also produced via the limiting reaction for the ^7Be buildup $^7Be(\alpha\gamma)^{11}C$. Boron production has traditionally been thought to be via the cosmic ray spallation process, but simple spallation produces an isotope ratio $^{11}B/^{10}B \sim 2.5$ whereas the observed (Cameron, 1982) isotope ratio is $^{11}B/^{10}B \sim 4$. Thus, there is the need for some process to augment ^{11}B production (Meneguzzi, Audouze and Reeves, 1972).

Earlier studies of Li production in supernovae (Epstein, Arnett and Schramm 1976) were used to limit Deuterium production but were not serious candidates for light element synthesis due to their use of a strong ion-shock which Weaver and Chapline (1974) had shown to be unlikely.

We also looked briefly at another supernova production process for ^7Li and ^{11}B, namely neutrino-induced reactions (Epstein, Colgate and Haxton, 1988). The high intensity neutrino burst can spall the carbon and oxygen nuclei leading to Lithium, Berylium and Boron production. Furthermore, neutrino spallation in the Helium zone can yield ^3He and ^3H which can react with the ^4He to build mass 7. Our preliminary examination of the cross sections involved in this neutrino mechanism suggests that the mass -11 yield will dominate over the mass -7 yield (removing one nucleon from ^{12}C is easier than removing several.) Furthermore, the mass-7 specific reactions take place in the helium zone where the neutrino flux is lower than in the carbon and oxygen zones, but the temperature is higher than in the hydrogen zone so that any mass-7 produced is more easily destroyed. Thus, although the neutrino-induced process could be for important at producing ^{11}B it should not be a significant source of ^7Li. Hartman, Hoffman, Haxton and Woosley (1988) are making a detailed exploration of this process so we will not comment further on it here. We will instead focus our attention on the thermonuclear production induced by shock heating in the hydrogen zone.

To explore our thermonuclear process we have taken 15 and 25 $M_\odot$ evolved stellar models and propagated supernova shocks through them. The maximum temperature resulting from the shock heating as well as the amount of ^3He still available in the appropriate zones varies with the velocity of the shock, the radius of the star, and the mass of the star. We have explored the dependences on these parameters in our models. It should be remembered that supernova progenitors may have different radii dependent on metalicity and/or mass loss as was illustrated by SN1987A. Thus exploring a range in parameters is necessary.

MODELS

The pre-supernova envelope structures through which we pass our shocks come from the evolution of 15 and 25 solar mass models with initial compositions, $X = 0.7, Z = 0.02$ (Pop I), and $^3He = 2.1 \times 10^{-4}$. The ^3He value was that used in an earlier study of ^3He depletion in massive stars (Dearborn, Steigman, and Schramm, 1985) and assumes that the Deuterium is processed to ^3He during the protostellar collapse phase. Our final ^7Li and ^{11}B abundances scale with our asssumed ^3He abundance. The models were evolved from the zero age main sequence into the core carbon burning phase, after which no additional nucleosynthesis occurs (in the envelope) prior to the core collapse.

The radii of red giant models are sensitive to the surface opacities and the mixing length. For this reason, the mixing length is often taken as a free parameter to fit the observed temperature of stars in a cluster. To examine the sensitivity of Li production to envelope density (or radius), we have considered red giant models with slightly different ages, as well as different mixing lengths (Table 1). While we find substantial Li and B production in all cases, the yield is density (radius) sensitive.

While the radius of a star at the end of its lifetime is quite uncertain, we can compare our models to observations. Lambert et al. (1983) examined the available observations of Betelgeuse, and found it to be a 15 solar mass star with a (log) radius between 13.63 and 13.67. Since it is a variable, the precise radius at the time of its core collapse cannot be pre-determined. Models a and b are, however, quite representative of Betelguese. The envelope contains 7.2 solar masses of hydrogen, and 11 solar masses total. The models are convective in the outer 10.5 $M_{\odot}$, and the ^3He mass fraction is a constant through this region at, approximately, 10^{-4}. Below the base of the convection zone the abundance of ^3He falls discontinuously to its equilibrium value outside the Hydrogen burning shell.

Since SN1987A, it has been evident that not all Type II supernovae originate from red giants. Our models all have blue loops during Helium burning, and the $25M_{\odot}$ model even ignites carbon in the blue. Nevertheless, our models evolve to the red before the core collapse occurs. In order to obtain an envelope structure that was similar to that which SN1987A must have had, we took models at a slightly earlier evolutionary phase, the end of helium burning and the beginning of carbon burning. Our models were still on a "blue loop" and had not yet returned to the red. Lithium production in such a star requires it to have had a red giant stage, in order to distribute the ^3He surviving in the outer envelope to the deeper regions. Following this, the blue loop causes some additional ^3He depletion in the deeper regions, but we find the enhanced density more than compensates for this. In this model, the envelope contained 18.5 solar masses of which 10.5 was Hydrogen.

METHOD OF CALCULATION

The peak temperature obtained from shock passage was determined from Hugoniot jump conditions. For a strong shock:

$$C_0 = (\gamma R\, T_0/\mu)^{1/2} \tag{3a}$$

$$\frac{P_1}{P_0} = \left(\frac{V}{C_0}\right)^2 \Big/ \left(\frac{\gamma+1}{2\,\gamma} - \frac{\gamma-1}{2\,\gamma}\,\frac{\gamma-1}{\gamma+1}\right) \tag{3b}$$

$$\frac{\rho_1}{\rho_0} = \frac{\gamma+1}{\gamma-1}; \qquad \frac{T_1}{T_0} = \frac{\gamma-1}{\gamma+1}\,\frac{P_1}{P_0} \tag{3c}$$

where the subscripts 0 and 1 refer to properties in the unshocked and shocked gas; $\gamma = c_p/c_v$ is the isentropic constant, R is the gas constant, C_0 is the sound speed in unshocked gas, μ is the mean molecular weight and, V is the velocity to which the gas is shocked.

After the shock passes we assume that a region cools as it expands freely, giving a time dependence for the temperature and density of:

$$\rho(t) = \rho_1 \left(\frac{R_0}{R_0 + Vt}\right)^3; \quad T(t) = T_1 \left(\frac{\rho(t)}{\rho_1}\right)^{\gamma-1}. \tag{4}$$

The results that we will present are for a single value of the isentropic exponent, $\gamma = 5/3$. Calculations with a lower value, $\gamma = 4/3$, resulted in slightly lower Li (10%) and B (40%) production in cases of interest (though Li production was considerably lowered, by 60%, in cases where it was already insufficient).

With the assumptions implicit in these equations we determined the conditions for nucleosynthesis from the velocity to which a given region of the envelope is accelerated by the shock passage. For this velocity, we turned to the work of Woosley and Weaver (1988) (hereafter W^2) and Weaver and Woosley (1980). In their detailed calculation of SN1987A, the initial velocity to which material in the hydrogen envelope is accelerated decreases linearly with mass from a peak value at its base. In their work, this peak velocity was near 5500 km/s, and it decreased to a minimum value near 2000 km/s (see fig 5 of W^2). Their earlier paper presented similar information for a 15 solar mass model with a red giant structure. Here, as might be expected from the steeper density gradient, the peak velocity at the hydrogen-helium interface was over 10,000 km/s, and the velocity decreased more quickly with mass.

From this behavior we assumed a profile of initial velocities that decreases linearly from a peak value at the hydrogen-helium interface to 2000 km/s at a position in the envelope chosen from W^2. Because the nucelosynthesis that we are interested in occurs near the base of the envelope where the velocity is near its peak value, we are not particularly sensitive to the assumed profile of initial velocities. The region of Lithium production in the red giant models occurs at a velocity exceeding 90% of the peak velocity, and between 75% and 95% of the peak velocity in the "blue loop" models (depending on shock strength).

The temperatures and densities determined in this manner were used to follow the nucleosynthesis from the time that the shock passes a point until the temperature there falls below a million degrees, and no further charged particle reactions can occur. The free expansion assumption allows the temperature to decrease more quickly than in detailed models, but this does not lead to dramatic differences. The primary effect of a slightly slower cooling time is to move the Li production region outward in mass. Arbitrarily doubling the cooling time always resulted in Lithium enhancements. In some cases, the Lithium yield was nearly twice what we will report. The slower cooling time reduced the boron enhancements.

The nucleosynthesis network was solved implicitly for the reactions given in table 2, and the time histories of the ^3He and ^7Li abundances were checked against an analytic solution. The rates used were taken from (Fowler, Caughlan and Zimmerman, 1975, 1988 FCZ II and FCZ III). We did not include the reaction $^7Be(e,\nu)^7Li$, because the electron capture rate was slow compared to the cooling time, and charged particle reactions are much more significant in the destruction of ^7Be. All ^7Be remaining at the end of the calculation (when $T = 10^6$) would then electron-capture to form ^7Li. We also excluded the $^3He(^3He,2p)^4He$ reaction, because it was much slower than the $^3He(^4He,\gamma)^7Be$ reaction for all but the short time spent at low temperatures after the $^7Li(^7Be)$ and ^{11}B had been produced. As with the ${}^7Be$, any ${}^{11}C$ remaining at the end of the calculation then converts to ${}^{11}B$.

RESULTS

Lithium and Boron production has been calculated for the envelopes described above with three assumed peak velocities (4000, 5000, and 6000 km/s); the detailed calculations of W^2 suggests that the higher velocities (5000-6000 km/s) may be more realistic. In addition, peak velocity of 10,000 km/s was used with models a and b. As we discussed above, models a and b are sensitive only to the peak value of the velocity assumed. In the more compact envelope models (d, e and to a lesser extent c), the velocity distribution was a little more important, but the core size and envelope structure of models d and e were well matched to the particular case that W^2 calculated. We, therefore, do not believe that this is a major source of uncertainty. The results of our calculations are given in Table 3.

In order to normalize our yields to an element produced in gravitational collapse supernova, we used iron. As Arnett, Schramm, and Truran (1989) point out, the iron yield per collapse should be roughly constant and (to the accuracy needed here) almost independent of the mass of the star, the outer envelope configuration, or the velocity profile. This is because the central core is so similar for different models (again to the accuracy appropriate here). From SN1987A we know that the iron yield is $\sim 0.07 M_\odot$ (Woosley 1987). In the recent past it was thought that Type II supernovae were not significant iron producers and Type I's were needed. However, Arnett, Schramm and Truran (1989) argue that $0.07 M_\odot$ of iron per collapse event is sufficient to explain the bulk of the iron in the Galactic disk and the contribution from Type I's is at **most** about 50%. Thus to a factor of 2 accuracy it is reasonable to use Fe as our normalizing element. We could, instead have used oxygen, but the oxygen yield is sensitive to the stellar mass.

To be a useful source of ${}^7Li$ and ${}^{11}B$, the ratios Li/Fe and B/Fe in the ejecta must be greater than or comparable to present values in the galaxy. The presence of Deuterium in the interstellar medium indicates that there must be some fraction of the disk material that is unprocessed since Deuterium is only made in the Big Bang and is destroyed in stars (Epstein, Lattimer and Schramm 1976). The present values are (Cameron 1982):

$$log(Li/Fe)_{\mathbf{Cameron}} \simeq -4.3 \pm 0.1; \text{ or by mass}: \ log \left[\frac{M(Li)}{M(Fe)}\right]_{\mathbf{Cameron}} = -5.2 \pm 0.1 \quad (5)$$

and

$$log\ (B/Fe)_{\mathbf{Cameron}} \sim -5.1; \text{ or by mass}: \ log \left(\frac{M(B)}{M(Fe)}\right)_{\mathbf{Cameron}} \sim -5.8 \quad (6)$$

However, Anders and Eberhart (1982) (see also Grevesse and Anders 1988) find values for B about a factor of 3 higher (the values for Lithium in these papers are similar to Cameron 1982) A "critical" yield of Lithium in a SN is

$$M(Li)_* \equiv \left[\frac{M(Li)}{M(Fe)}\right]_{\mathbf{Cameron}} M(Fe)_{SN} \quad (7)$$

Thus, for lithium,

$$log\ M(Li)_* = -6.3 \pm 0.1 \quad M(Li)_* \gtrsim 4 \times 10^{-7}\ M_\odot \tag{8}$$

Similarly, for boron we find.

$$log\ M(B)_* = -6.5 \pm 0.1, \quad M(B)_* \gtrsim 3 \times 10^{-7}\ M_\odot \tag{9}$$

Interesting values are probably within a factor of 2 or 3 of these critical values. In our calculations, the stronger, more realistic shock (6000 km/s) produces sufficient Li and B in all of the models. (See Figures 1A and 1B.)

There is a clear distinction, however, between the behavior of the extended red giant models, a and b, and the less expanded or blue models, c, d, and e. This is most noticeable in the Li/B production ratio for various shock strengths. In models a and b, the convection zone has carried the ^3He to very near the bottom of the envelope. Below this point the ^3He abundance is very low. The lithium production peaks at the base of the convection region because of the high ^3He abundance there, and decreases outward because of the rapid density drop. In both of these models, the stronger shock converts more ^3He into ^7Li, but in no case is the ^3He abundance substantially lowered (in the Lithium production region.) In the weaker shock (4000 km/s) case, the ^{11}B is produced in a ^3He poor region below the base of the convection zone. Boron production here is limited by the depletion of the ^3He, and a stronger shock can produce no more ^{11}B in this region. A stronger shock does allow a second ^{11}B production region that peaks just below the ^7Li production region. In this case, the ^{11}B abundance has a double peaked structure. While additional ^{11}B is being produced by the stronger shock, the increase in the ^7Li production is even greater, leading to high Li/B ratios.

For initial velocities > 6000 km/s, the Lithium production sensitivity to shock strength decreases. At this point, the shock is strong enough to produce high temperatures in the ^3He rich region and produce a Lithium peak. Increasing the shock strength to produce initial velocities of 10,000 km/s results in only a doubling of the Lithium by moving out and broadening the peak. The higher velocities do, however, lead to dramatic Boron enhancements (20X) for reasons discussed below.

In models c, d, and e, the convection zone had distributed ^3He to a deep region during an earlier phase as a red giant and retreated during a blue excursion. The higher envelope temperatures during the blue loop reduces the abundance of the ^3He by factors as much as 10, (to 10^{-5}), but this is still more than enough to produce significant amounts of Lithium and Boron. Additionally, the higher density in the condensed models more than compensates for the decreased ^3He abundance. In these models, the ^3He profile is much more continuous than in the extended models above. The ^{11}B production begins at a deeper level and continues outward to the ^7Li production region. The ^{11}B production is not limited in the deeper regions by ^3He depletion and, with a stronger shock, the ^7Li producing region moves out leaving behind a larger ^{11}B rich region. This results in a decreasing Li/B ratio with shock strength. All of these models (c, d, and e) produce adequate amounts of ^7Li, and only the weak shock case of the red giant, model c, produces less than adequate ^{11}B.

Our results indicate that extended red giants like Betelguese will be modest net producers of ^7Li and ^{11}B. Supernovae originating from less extended red giants or blue stars will produce a tremendous amount of ^7Li and ^{11}B (enhancements $> 100X$), allowing substantial dilution. The high ^{11}B production in these objects may, in fact, require slightly weaker shocks (with Vmax=5000 km/s) to avoid over-production. This might be used as a constraint on our models. Such supernovae may have been more common during the early evolution of our galaxy. when the heavy element abundance was low. Even for the pre-supernova configurations of a more extended star (like Betelguese), the Li and B yields will still be significant.

CONCLUSIONS AND OBSERVATIONAL IMPLICATIONS

Since ^7Li and ^{11}B can be made in significant amounts in core collapse supernova, where the bulk of the heavy elements are synthesized, they should track the evolution of oxygen, iron, etc. in the Galaxy. (We have ignored the complication of Type I production of Fe since as Arnett, Schramm, and Truran (1989) argue at least 50% of all Fe comes from collapse events. However, our models can produce sufficient Lithium that dilution with Fe from Type I's is allowable). The high yields of Li and B, relative to Fe, are a good indication of the success of our model. In addition, the excessively high yields of Boron for the blue compact envelope models may constrain the number of blue progenitor, Type IIs (i.e. models d and e). This might have important implications for the relative numbers of such lower luminosity Type IIs.

Discussion of detailed Li and B evolution in the Galaxy must await galactic evolution models. However, a few conclusions can already be made. In particular, we expect ^7Li and ^{11}B to track oxygen and iron. For Pop II stars, the oxygen and iron abundances are sufficiently low that supernova produced Li would have been negligible compared to the primordial Big Bang produced ^7Li. However, by the time the metals have built up to near their Pop I value of $Z \simeq 0.02$ we would expect ^7Li and ^{11}B to have also saturated at their Pop I values.

For the LMC with heavy element mass fraction $Z \sim Z_{\odot}/3$, (c.f. Danziger 1988) we might expect $Li \sim (Li)_{PopI}/3$ which is somewhat larger than current reported limit (Sahu, Sahu and Pottasch 1988; Baade and Magain 1988) but uncertainties due to grain depletion remain before a definitive test can to be made (Steigman 1989). Since ^6Li and ^{10}B are made via cosmic ray spallation rather than direct supernovae production, they might not grow as fast, as ^7Li and ^{11}B; thus, older objects would be expected to have high $^7Li/^6Li$ and $^{11}B/^{10}B$ ratios. The difference between the $^7Li/^6Li$ ratio of 12 in the solar system and $\gtrsim 25$ in the direction of Zeta Ophiucus may be a demonstration of the supernova enrichment of ^7Li in the Sco-Cen Association.

We also would expect young supernova remnants to show enrichments in ^7Li and ^{11}B, with blue progenitor stars yielding higher ^{11}B and red giants higher ^7Li. The broad lines (and unknown ionization states) in supernova ejecta may make for observational difficulties, but the enchancements could be huge. Spectra of SN 1987A should be searched for evidence of Li and/or B.

Supernova shocks at the base of the hydrogen envelope also can have other interesting effects. For example, neutron emission from $^{13}C(\alpha n)^{16}O$ and $Ne - Na$ cycling ng will also yield nucleosynthetic effects. These will be explored in a subsequent paper (Brown, et al. in preparation).

Galactic evolution models that require Li initally above the observed Pop I value to try to fit high Ω_{baryon}, quark-hadron fluctuation inspired, nucleosynthesis models (Applegate et al 1987; Alcock et al 1987) could have difficulties if this production mechanism is verified. With this mechanism primordial Lithium would be augmented by supernovae, but primordial Deuterium would not. Since Deuterium is preferentially destroyed in stars relative to Lithium, then the presently observed Li/D ratio would be greater than the ratio $[(Li)_{\text{primordial}} + (Li)_{\text{SN}}]/(D)_{\text{primordial}}$. Present models are only consistent if $(Li)_{\text{SN}} \ll (Li)_{\text{primordial}}$ since even in high Ω_{baryon} models $(Li/D)_{\text{primordial}}$ is at best comparable to the current Li/D ratio.

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Table 1

Envelope Models

Model	Mass	α	Log(R)	Log(Te)	Log(ρX.5)
a	15	1.4	13.66	3.559	-2.83
b	15	1.6	13.62	3.578	-2.86
c	15	1.4	13.42	3.607	0.90
d	25	1.4	12.28	4.357	1.00
e	25	1.4	12.78	4.101	-0.05

(Mass is in solar masses, α is the ratio of the mixing length to pressure scale height, R is the stellar radius in cm, T is the preshock effective temperature in $^{\circ}K$, and $\rho X.5$ is the density when the hydrogen mass fraction $X = 0.5$. This density occurs near the region where Lithium production occurs.)

Table 2

Reactions included in network

$^{3}He\ (\alpha\gamma)\ ^{7}Be$
$^{7}Be\ (p\ \gamma)\ ^{8}B \rightarrow 2\alpha$
$^{11}C\ (p\ \gamma)\ ^{12}N \rightarrow ^{12}C$
$^{11}C\ (\beta\nu)\ ^{11}B$
$^{11}B\ (p\ \alpha)\ 2\alpha$
$^{7}Be\ (\alpha\gamma)\ ^{11}C$

Table 3

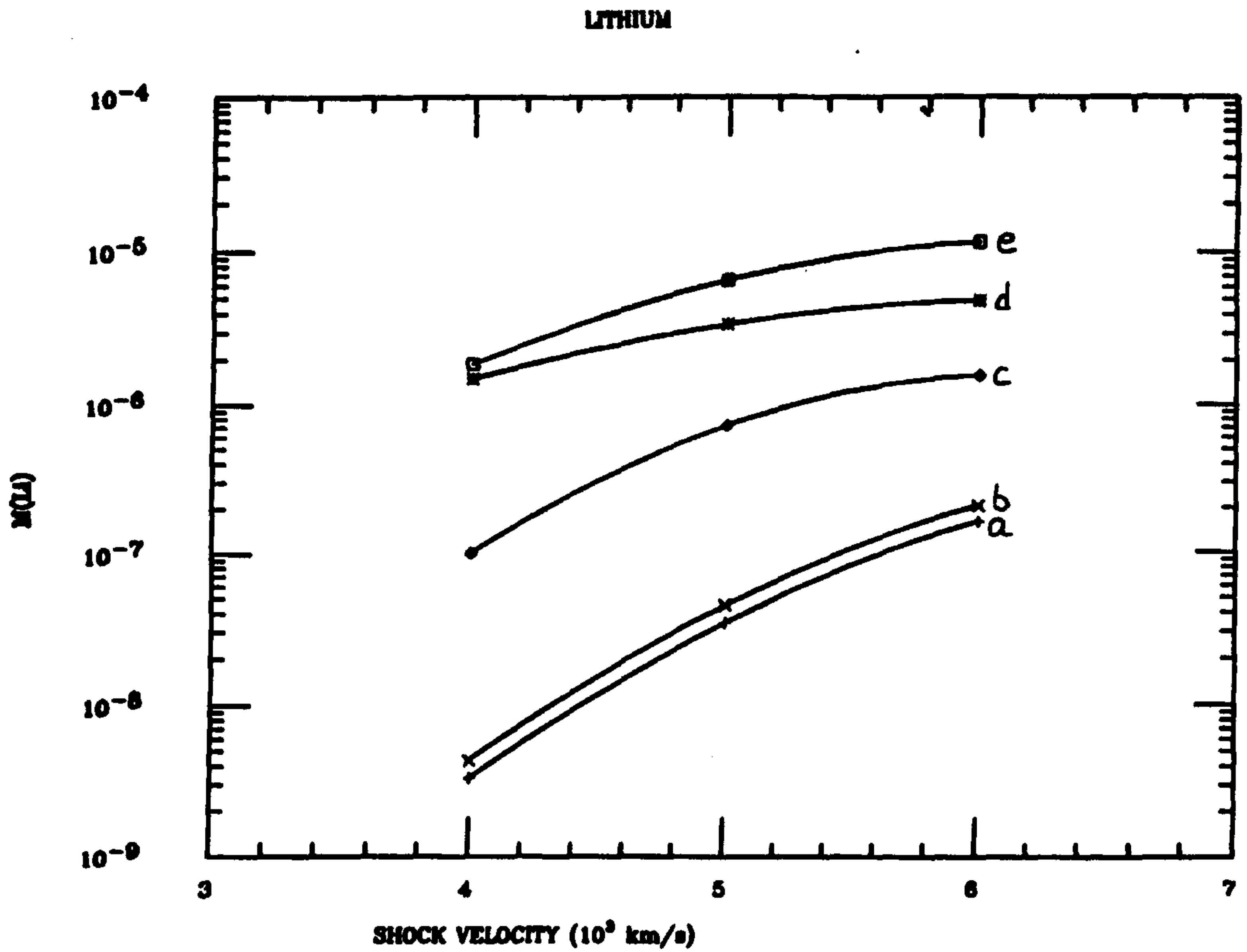
Maximum Velocity (km s[1])

Model Log Radius (cm)		4000.	5000.	6000
a	Li	3.3E-9 $M_\odot$	3.4E-8 $M_\odot$	1.6E-7 $M_\odot$
13.66	B	2.3E-9 $M_\odot$	6.4E-9 $M_\odot$	2.7E-8 $M_\odot$
	Li/B	2.3	8.5	9.4
	M(Li)/M(Fe)	4.8 E-8	4.9 E-7	2.3 E-6
	M(B)/M(Fe)	3.3 E-8	9 E-8	3.9 E-7
b	Li	4.4E-9 $M_\odot$	4.5E-8 $M_\odot$	2.1E-7 $M_\odot$
13.62	B	5.7E-9 $M_\odot$	1.1E-8 $M_\odot$	4.3E-8 $M_\odot$
	Li/B	1.2	6.6	7.5
	M(Li)/M(Fe)	6.2 E-8	6.4 E-7	3.0 E-6
	M(B)/M(Fe)	8.1 E-8	1.5 E-7	6.2 E-7
c	Li	1.0E-7 $M_\odot$	7.2E-7 $M_\odot$	1.6E-6 $M_\odot$
13.42	B	2.6E-9 $M_\odot$	4.4E-7 $M_\odot$	4.2E-6 $M_\odot$
	Li/B	62.0	1.6	0.6
	M(Li)/M(Fe)	1.4 E-6	1.0 E-5	2.3 E-5
	M(B)/M(Fe)	3.7 E-8	6.2 E-6	6.0 E-5
d	Li	1.9E-6 $M_\odot$	6.6E-6 $M_\odot$	1.2E-5 $M_\odot$
12.28	B	4.5E-7 $M_\odot$	1.8E-5 $M_\odot$	6.8E-5 $M_\odot$
	Li/B	6.5	0.6	0.3
	M(Li)/M(Fe)	2.7 E-5	9.4 E-5	1.7 E-4
	M(B)/M(Fe)	6.4 E-6	2.6 E-4	9.7 E-4
e	Li	1.5E-6 $M_\odot$	3.4E-6 $M_\odot$	4.9E-6 $M_\odot$
12.78	B	5.9E-7 $M_\odot$	1.7E-5 $M_\odot$	6.7E-5 $M_\odot$
	Li/B	3.9	0.3	0.1
	M(Li)/M(Fe)	2.1 E-5	4.9 E-5	7 E-5
	M(B)/M(Fe)	8.5 E-6	2.4 E-4	9.6 E-4

Li and *B* are the total mass of these elements in the envelope, and the abundance ratios are by number, averaged over the entire ejecta. We have taken M(Fe)=$0.07 M_\odot$ "Interesting" values are mass yields of a few 10^{-7} or more for both *Li* and *B*. Observed *Li/B* ratios range from ~ 2.6 to ~ 8. Values below this may impose constraints on the frequency of such supernovae.

FIGURE CAPTIONS

Figure 1A	Lithium yields in $M_\odot$ versus peak shock velocity
Figure 1B	Boron yields in $M_\odot$ versus peak shock velocity


LITHIUM
M(Li)
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
3
4
5
6
7
SHOCK VELOCITY (10^3 km/s)
a
b
c
d
e

BORON